CARRIE M. LEWIS, LON A. COUILLARD, PATRICIA J. KLAPPA, AND TERRENCE D. VANDENBUSH

Lead Water Service Lines: Extensive Sampling and Field Protocol Protects Public Health

A PILOT STUDY IN MILWAUKEE, WIS., ASSESSED LEAD LEVELS BEFORE AND AFTER WATER MAIN REPLACEMENT AND LED TO A NEW SAMPLING AND COMMUNICATION PROTOCOL FOR ADDRESSING POSSIBLE INCREASED LEAD AT THE TAPS OF CUSTOMERS WITH LEAD SERVICE LINES.

In Milwaukee, Wis., there are approximately 70,000 residential structures with water service lines made of lead—about 40% of total service lines in the city. The Milwaukee Water Works (MWW) has implemented successful corrosion control treatment since 1996 to reduce lead leaching into drinking water. The 90th percentile lead concentration in compliance sampling before the addition of orthophosphate was 28 µg/L; following implementation of corrosion control, it reached a minimum of 4.6 µg/L in 2002 and has been at or below 8.2 µg/L through the most recent sampling period. Continued compliance with the Environmental Protection Agency's (USEPA's) Lead and Copper Rule demonstrates the effectiveness of corrosion control treatment.

MWW was aware of research results that linked disturbances of lead service lines (LSLs) with increased levels of lead at the customer's tap. This was of particular concern to MWW because planning was underway to increase the total length of water mains replaced annually from approximately 5 to 15 mi initially and then up to 20 mi within four years. The original plan for the 15 mi to be replaced in 2016 affected approximately 1,700 service lines, 500 of which were LSLs.

PILOT STUDY OF REPLACEMENT PROJECTS WITH LSLs

In collaboration with the Milwaukee Health Department (MHD), a pilot study was conducted in 2015 to assess lead levels at customers' taps before and after their LSLs were severed during water main replacement projects. At that time it was MWW's practice to reconnect LSLs to new water mains during water main replacement, leaving the original LSLs in service. The original LSL was severed near its connection to the original main, a piece of copper pipe was spliced in, and the copper pipe was reconnected to the new (replaced) water main. The excavation to access the original LSL was only a few feet long, perpendicular to and in direct proximity to the water main; the rest of the LSL was not exposed.

Residents of 21 single-family homes with LSLs within the limits of the water main replacement project were invited to participate; residents of six of those homes volunteered. Three sets of samples were collected from each home—the first to represent lead levels at the premise before the water main replacement work began; the second taken as soon as possible after the service line had been severed and reconnected, and the home was receiving water from the new water main (usually the following morning); and a third set of samples three to six weeks later.

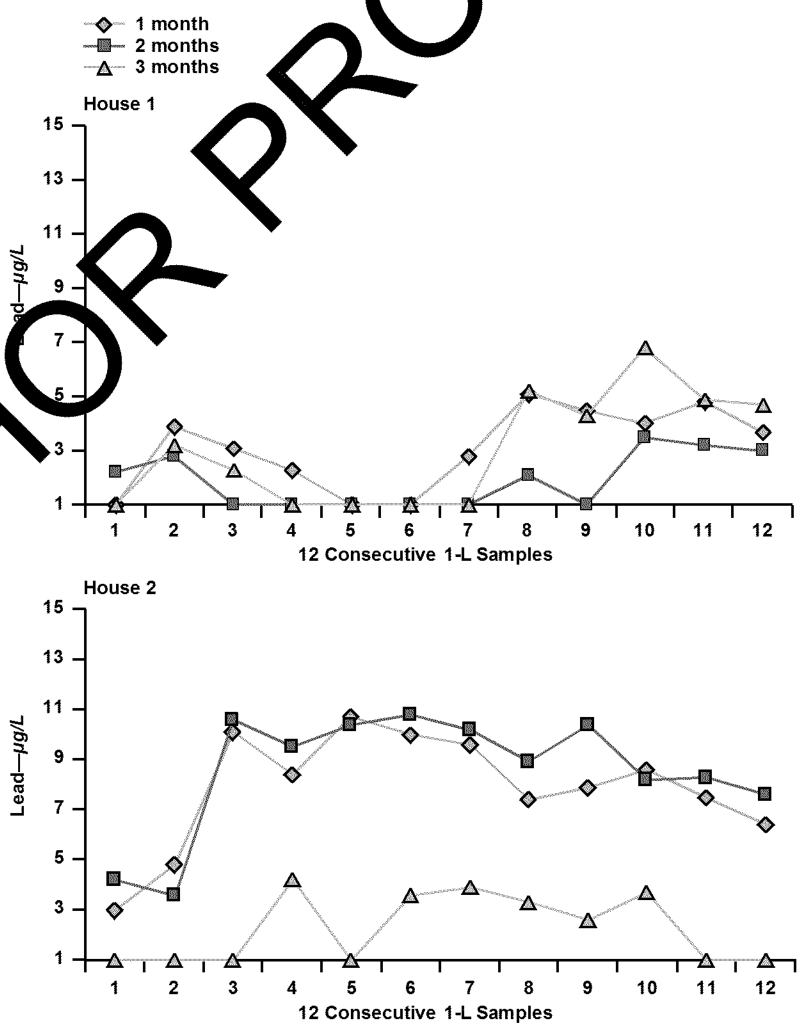
Each set of samples consisted of 12 consecutive 1-L samples collected from the kitchen tap after the water had remained motionless in the home's pipes for at least 6 h following the protocol of Cornwell and Brown (2015). A 13th 1-L sample also was collected after a 3-min flush to represent water in the distribution system. A total of 234 samples were collected. Samples were analyzed by graphite furnace atomic absorption spectrophotometry with a detection limit of 2 µg/L. A value of 1 µg/L was used in calculations and graphs when lead was not detected.

The project plan also included risk messaging developed by the MHD to use when transmitting sample results to residents. The risk messaging was tailored to levels of lead in the samples and the presence/absence of vulnerable populations at the homes.

Repeated sampling from homes not affected by construction provided information on the variability of lead levels in the absence of construction activities and a baseline against which to evaluate the LSL disturbance in the water main replacement projects. Data collected from Milwaukee homes sampled once a month for three consecutive months as part of Water Research Foundation Project 4569 (Cornwell & Brown 2015) were used.

In the two examples shown in Figure 1, each home has a distinctive pattern of lead levels in the 12 consecutive 1-L samples. However, there is variability in the levels of lead between sampling dates at the same house. This inherent variability needs to be recognized when interpreting results of samples before, during, and after construction projects.

FIGURE 1 Lead levels in homes sampled for three months in a row, 2014

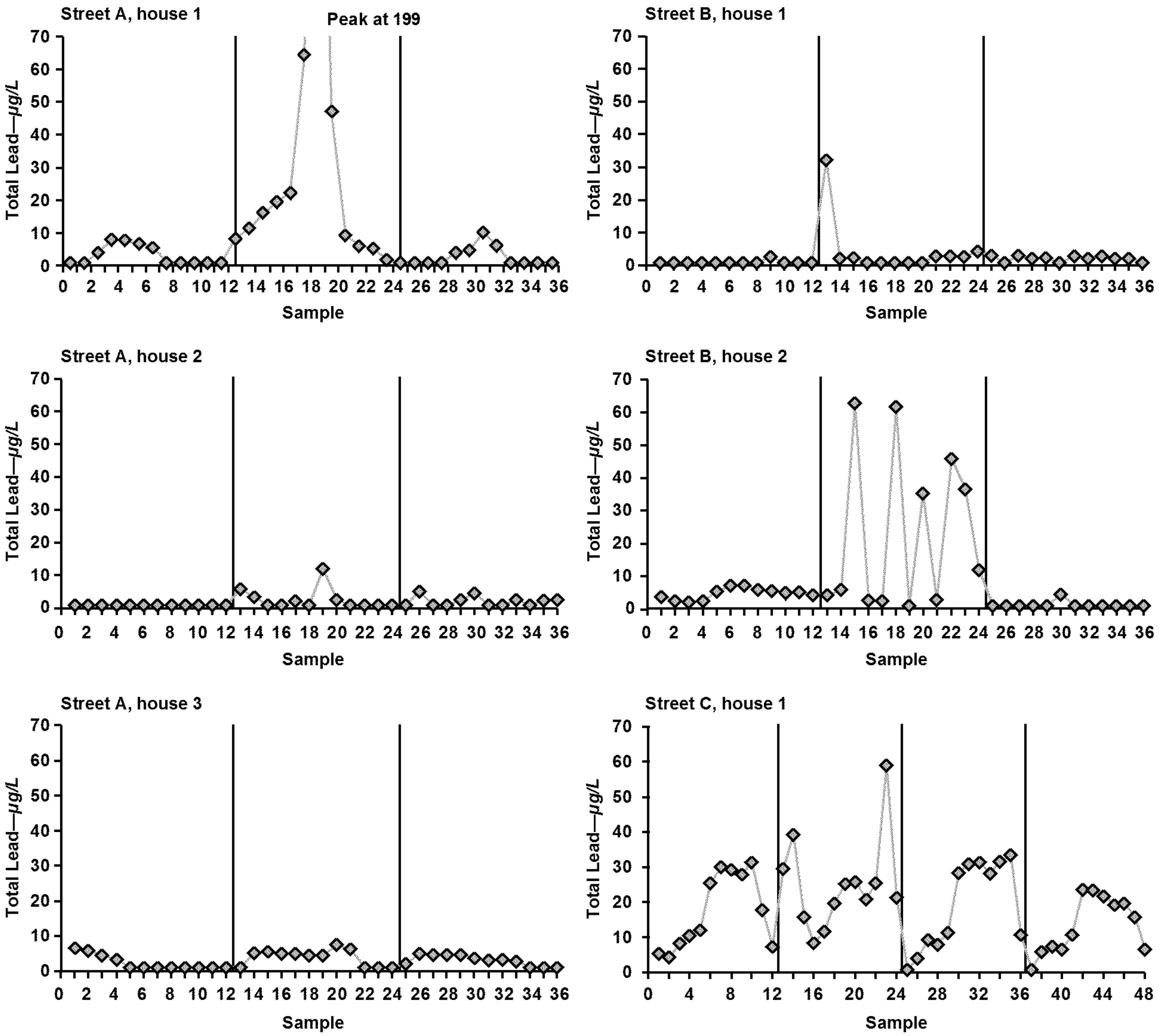


Lead levels at individual homes demonstrate variability even in the absence of construction. Each house has a distinctive pattern, but different lead levels, when sampled once per month for three months in a row in 2014. Lead below the detection limit of 2 µg/L is shown as 1 µg/L.

In contrast, lead levels at the tap in each of the homes where the LSL was severed for water main replacement showed marked effects the day after the severed LSL was returned to service. Figure 2 shows that no home was unaffected. Regardless of the pattern of lead levels in the 12 consecutive samples, the sample set collected approximately 24 h after the LSL had been severed and reconnected showed higher levels of lead. In samples collected four to six weeks later, lead levels were similar to levels before the disturbance.

On the basis of these findings, MWW suspended water main replacements that would have affected LSLs in late 2015, and the goal of replacing 15 mi of water main in 2016 was met by substituting projects that included only copper service lines. However, work to respond to emergency water leaks could not be suspended, and other construction projects that may affect LSLs were being scheduled for the 2016 construction season. The Water Quality Section of MWW and the Disease Control and Environmental Health Section of the MHD worked together to develop strategies to

FIGURE 2 Lead levels measured at the tap before, one day after, and one month after LSLs were severed and reconnected to a new water main during projects completed in 2015



LSL—lead service line

Three sets of samples were collected from each home. The first 12 data points in each graph are the 12 consecutive 1-L samples that were collected before work commenced. Data points 13–24 represent the 12 consecutive 1-L samples that were collected 24 h after the lead service was connected to the new water main. Data points 25–36 represent the 12 consecutive 1-L samples that were collected four to six weeks later. Street C, house 1, had an additional round of sampling collected at seven weeks, after a second whole-house flush.

protect public health during necessary work and to collect water quality data to inform policies and practices for future construction. Colleagues at the Wisconsin Division of Health Services, Wisconsin Department of Natural Resources, and the USEPA provided valuable input and guidance during this process.

CONSTRUCTION PROJECTS' IMPACT ON LEAD AT THE TAP

Construction activities within the project limits that may affect lead levels at the customer's tap were identified:

- **Partial LSL replacement.** Replace the utility-owned portion of the LSL in response to a leak, including installing a nylon washer (to prevent galvanic corrosion) at a new lead-free corporation stop, copper tubing for the utility-owned portion of the service line, a new curb stop, and a second nylon washer at the outlet of the curb stop.
- **Sewer main replacement.** A trench is excavated parallel to and a few feet away from the water main down to and exposing the water services. The trench is deepened another few feet, and the sewer main is "threaded" underneath the water service lines. The sewer is connected, and the trench is backfilled and material compacted, usually all in a single day. LSLs on only one side of the water main are disturbed.
- **Water meter inlet valve replacement.** In order to repair a leaking or inoperable meter inlet valve, the LSL is severed just upstream of the water meter in the basement of the premise. About a foot of copper tubing is connected between the LSL and the water meter. This work is performed by a plumber contracted by the property owner.
- **Road reconstruction.** This included breaking up and removing concrete road surface, curb, gutter, and driveway approaches followed by placing and compacting new material. LSLs remained buried under at least 5 ft of cover during these projects.

Response to leaking LSLs was deemed the top priority because of their frequency (average of five per week in the MWW service area) and the extensive disturbance of the LSL necessary to stop the leak—typically complete excavation and severing of the service line. A field protocol (described later) to protect public health was immediately developed and implemented.

Overview of results. The following is based on 177 sets of water samples collected from 89 residences between February and August 2016. Each set of samples consisted of 12 consecutive 1-L samples collected after a minimum 6-h stagnation and a 13th well-flushed sample. There are 450 baseline samples from residences unaffected by construction, 1,245 samples from partial LSL replacements performed to address leaks, 260 samples from sewer main replacements, 169 samples from meter inlet valve work, and 167 samples from road reconstruction projects. When the 234 samples from the six homes in the 2015 pilot study are added, a total of 2,525 samples are included in this analysis.

> The Milwaukee Water Works was aware of research results that linked disturbances of lead service lines with increased levels of lead at the customer's tap.

Results by type of construction. It is useful to review the sample results in three groups: the first 1-L sample (match to current Lead and Copper Rule sample requirements), the 12 sequential 1-L samples, and the 13th well-flushed samples. For all types of construction, much more information is gained in the series of 12 consecutive 1-L samples than is available from the first 1-L sample alone, as shown in the 2015 pilot and baseline data in Figures 1 and 2. When the data are aggregated, those nuances are largely lost; however, some general observations can still be made.

As summarized in Table 1 and Figure 3, construction practices that involved excavation and severing LSLs had the highest proportion of samples with lead levels greater than 15 µg/L. Sewer main replacements, water meter inlet valve replacements, and homes without construction had similar proportions of samples with lead levels greater than 15 µg/L. Only road reconstruction projects had no samples with lead measured over 15 µg/L. Well-flushed samples had lower maximum and average lead levels in all samples except those from the 2015 pilot study. (There was a single sample result of 328 µg/L, considered an anomaly as three follow-up well-flushed samples all showed lead below detection.) In all except the no-construction and road-reconstruction samples, there were instances in which a single sample in the series was unusually high. These single high results were not confirmed upon resampling.

Results by sample sequence. The average and 90th percentile of the first 1-L sample for all sample sets combined are 9.1 and 10 µg/L, respectively. This compares reasonably well with the average and 90th percentile of all 12 consecutive liters for all sample sets at 5.8 and 11 µg/L, respectively. The most striking attribute of the data aggregated by sample sequence is the obvious benefit of flushing. The well-flushed samples have the highest proportion of samples with lead below detection (74%) and the lowest proportion with lead greater than 15 µg/L (2%). The average and 90th percentile of the

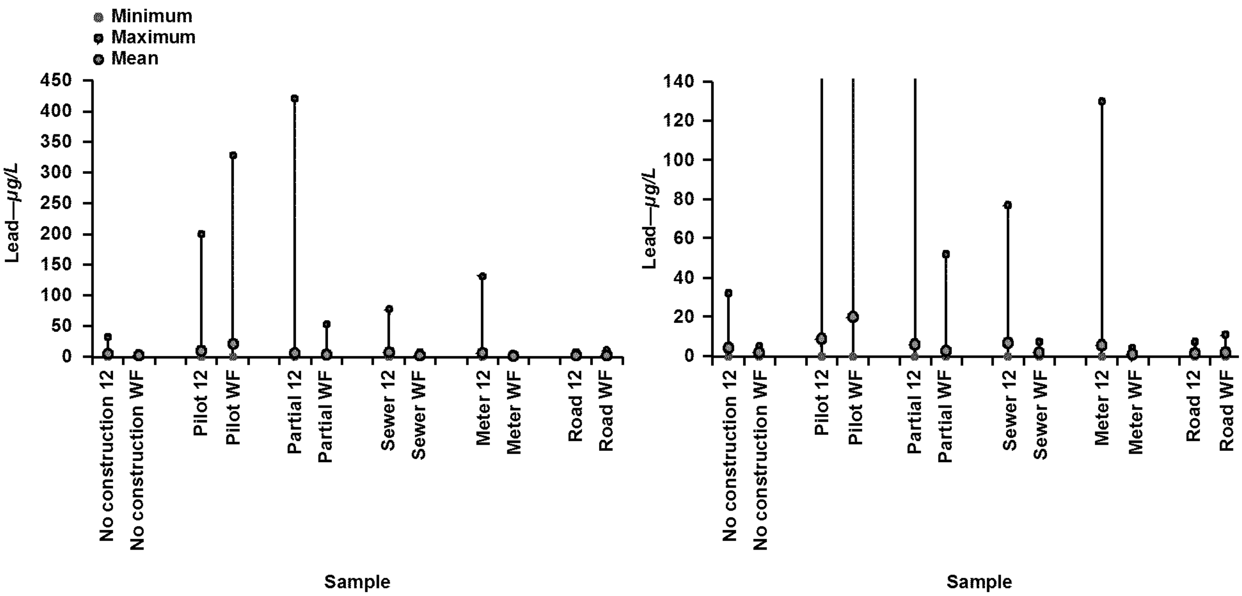
TABLE 1 Attributes of lead levels measured in samples by type of construction

Type of Construction	Sample Sequence	Number of Samples	Samples With Lead Below Detection (<2 µg/L) %	Samples With Lead >15 µg/L %	Maximum Level of Lead in All Samples *µg/L*	Average Lead Concentration in All Samples *µg/L*	Median Lead Concentration in All Samples *µg/L*
No construction	First liter	36	61	0	16	2.8	<2
	Sequential 12 liters	432	44	3	32	4.3	2.8
	Well-flushed	18	83	<1	328	20	<2
Connect original service (2015 pilot study)	First liter	18	39	0	32	6.1	2.7
	Sequential 12 liters	216	38	19	199	9	2.8
	Well-flushed	18	56	<1	328	20	<2
Partial LSL replacement	First liter	96	40	<1	420	14	2.8
	Sequential 12 liters	1,149	50	7	420	6.1	<2
	Well-flushed	96	75	<1	52	2.8	<2
Sewer main replacement	First liter	20	25	5	37	4.9	2.9
	Sequential 12 liters	240	10	3	77	6.7	5.4
	Well-flushed	20	75	0	7.3	<2	<2
Water meter inlet valve replacement	First liter	13	31	8	40	5.9	3.0
	Sequential 12 liters	156	48	5	130	5.6	<2
	Well-flushed	13	85	0	4.2	<2	2.0
Road reconstruction	First liter	12	67	0	4.4	<2	<2
	Sequential 12 liters	155	68	0	7.3	<2	<2
	Well-flushed	12	83	0	11	2.0	<2
Overall	First liter	195	43	4	420	9.1	2.2
	Sequential 12 liters	2,348	45	6	130	5.8	2.3
	Well-flushed	177	75	2	328	6.1	<2

LSL—lead service line

For Table 1, a value of 1 was used to calculate average and median when the sample result was below the detection limit of 2 µg/L.

FIGURE 3 Minimum, maximum, and mean lead in 1-L samples by type of construction



12—12 sequential samples, WF—all well-flushed samples well-flushed samples are 4.3 and 5.0 µg/L, respectively. These data are summarized in Table 2.

Results by time elapsed after work: paired sample analysis. Drinking water sample collection during sewer main replacement projects was done in the same fashion as previously described before construction and at approximately two weeks, one month, two months, and three months after the construction. The Wilcoxon signed-rank test was used to determine any differences in paired samples. Two weeks after the sewer work was completed, lead levels were essentially back to preconstruction levels as summarized in Table 3.

Compared with samples collected before construction, lead levels at houses 2 and 3 were not significantly different on any of the four follow-up samplings. House 1 was significantly higher only at the one-month and three-month samplings, and even then, the average of the 12 samples was 6.5 and 6.7 µg/L, respectively. House 4 had a significantly higher average lead level in the 12 sequential samples on the day after the construction was performed. Lead levels at that home were back at preconstruction levels in the two-week, one-month, and two-month sample sets. For house 4 at three months, the average of the 12 consecutive samples (7.8 µg/L) was significantly different from before construction (average of 5.2 µg/L) but was still well below the USEPA action level of 15 µg/L.

Results by total mass of lead released. Another way to examine results between types of samples or at a single location over time is on the basis of the total mass of lead released. The mass of lead in all 12 sequential 1-L samples, in which mass equals the measured concentration times sample volume, was added to yield the total micrograms of lead per 12 L. Figure 4 shows results for eight residences that had partial LSL replacements performed to address leaks. Lead levels dropped markedly after one month for all properties.

CHANGING PROTOCOL

MWW and MHD, on the basis of the results of the 2015 pilot study, developed a written sampling and risk communication protocol to respond to LSL leaks in anticipation that fixing the leak could expose residents to increased lead at their taps (MWW 2016). The protocol was based on the recommendations of the Lead and Copper Working Group to the National Drinking Water Advisory Council (Lead and Copper Working Group 2015). The objective was to protect residents' health while and after the leak was fixed, and to use the opportunity to educate residents about lead in water and collect data about the effects of the repairs at their taps. The following steps were included in a written protocol/script:

1. Provide information and risk messaging to residents/owners regarding the likely presence of an LSL, the leak, and what work would be done to address the leak. The owner is strongly encouraged to replace the privately owned portion of the LSL at the same time as the utility-owned portion to better protect the health of the residents and to potentially save money during repairs. A diagram of a water service line from water main to building basement is used in the explanation.
2. Determine the presence of any vulnerable populations at the home and share that information with the MHD. A form is provided for the MWW employee to document the interaction with the resident and to transmit the information to the MHD.

TABLE 2 Characteristics of the data sets by sample sequence

Sample Sequence	Number of Samples	Samples With Lead Below Detection (<2 µg/L) %	Samples With Lead 2–15 µg/L %	Samples With Lead >15 µg/L %	Average µg/L	90th Percentile µg/L
First liter	159	39	56	5	9.1	10
Sequential 12 liters	1,916	45	48	7	5.8	11
Well-flushed	159	74	24	2	4.3	5.0

TABLE 3 Wilcoxon signed-rank comparison of four homes sampled before and after a sewer main replacement project that exposed LSLs serving the properties

Sample Location	Average Lead Concentration Before Construction µg/L	Average Lead Concentration Before Construction Compared With Time Elapsed After Construction µg/L				
		One day	Two weeks	One month	Two months	Three months
House 1	3.8	2.4	2.5	6.5	3.2	6.7
House 2	11	8.3	6.5	5.1	8.5	9.6
House 3	6.2	4.4	8.5	4.4	4.2	5.9
House 4	5.2	23	8.9	5.6	1.9	7.8

LSL—lead service line

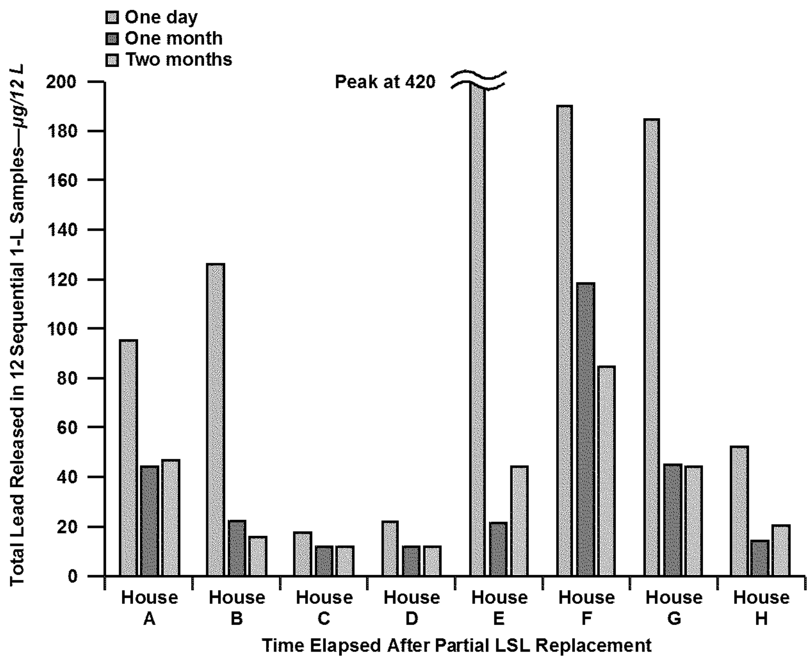
The numbers in the cells are the average concentration of lead in the 12-sample series for that sampling date. The data sets in the green-shaded cells are significantly lower than, or not significantly different from, the data set collected before the sewer main construction. The data sets in the brown-shaded cells are significantly higher than the data set collected before the construction.

3. Offer the resident/owner a filter certified to remove lead from water used for drinking and cooking during and after construction.
4. Take special precautions for locations with a focus on children (e.g., a day-care center or school). In these cases, a larger supply of water, such as an office-type water dispenser, is offered for drinking and cooking. Day-care personnel contact the supplier directly whenever replenishment is needed, and the MWW is billed for the service. A hose connection with proper backflow protection to a neighboring building or to a nearby hydrant is used so the premise will have water for nonpotable uses such as bathing, cleaning, and sanitation during the construction period.
5. Emphasize the importance of aggressively flushing the building's plumbing after LSL replacement. This is explained verbally and via written documents provided before work starts. The whole-house flushing technique described in Cornwell and Brown (2015) is used. After the work is completed, contact is again made with the residents to remind them to flush. A "Flush your household plumbing as soon as possible" door hanger is left if no one is home. (The message to flush has been generally well received and, fortunately, Milwaukee is not in a drought situation and water is relatively inexpensive—a 30-min flush of four taps costs approximately 16 cents.)
6. Offer to have lead samples analyzed at no cost to the residents and request their cooperation to help MWW collect data. If residents agree to participate, a MWW Water Quality staff member comes to the home and explains how to collect samples; shows a short video (MWW 2015) to demonstrate the technique; and delivers written sample instructions, chain-of-custody forms, and sample bottles. The sampling strategy of 12 sequential 1-L samples after 6 h of stagnation followed by a 13th "well-flushed" 1-L sample is used. Samples are collected as soon as possible after the work is completed (usually the following morning) and again at one month, two months, and sometimes three months after the LSL replacement.
7. All aspects of the interaction with the residents are documented, including their responses to questions about replacing their side of the service, interest in sampling, acceptance of a lead-removal filter, and any special circumstances.

In response to a leak, MWW now replaces (and no longer repairs) the utility-owned portion of the LSL. If owners opt to replace their portion as well, efforts are made by MWW to coordinate with the owner's contractor. At the time of this writing, replacement of the privately owned portion of the LSL was not mandatory, and there was no mechanism in place to help property owners with the cost of replacing their portion. Instead, MWW opted to partially replace LSLs that were leaking to reduce the likelihood that the LSL would be disturbed during future repairs.

Sample results were transmitted to residents, usually within a week, in a letter that explained the reason for the sampling, that the 12 sequential samples represented water in the building plumbing, and that the 13th sample represented water in the water main. The risk messaging was based on the lead levels in all 12 sequential samples, the 13th well-flushed sample, and presence/absence of vulnerable populations. It described the importance of flushing water before use, using water only from the cold-water tap for cooking and drinking, and regular removal and cleaning of aerators, and included guidance on use of the certified lead-removal filter.

FIGURE 4 Total mass of lead released after partial LSL replacements at eight residences in 2016



LSL—lead service line

The MHD reviewed all results and made phone contact with homes that had vulnerable populations or that had any sample result greater than 15 µg/L whether or not vulnerable populations were present. In the rare cases in which lead was detected at levels greater than 15 µg/L (13 samples), residents were advised to perform another whole-house flush, and immediate resampling was offered.

Protocols for other types of construction. In advance of the 2016 construction season, the field protocol that was developed for LSLs was adapted for each of the construction types noted previously and was modified repeatedly as sample results became available and the understanding improved of how the construction may affect lead at the customer's tap. The information from the series of 12 sequential samples plus the well-flushed sample was very valuable in risk messaging.

For sewer main replacement projects, residents on the side of the street where the LSLs are exposed receive letters and lead-awareness and best-practices information, and they are offered filters certified to remove lead. The importance of flushing after completion of construction is emphasized. Residents on the side of the street where the LSLs are not disturbed receive lead-awareness and best-practices information. Residents of streets where reconstruction projects are scheduled receive lead-awareness and best-practices information. Residents of properties where LSLs are severed for water meter inlet-valve replacement (or other repairs affecting the LSL) receive lead-awareness and best-practices information, and conducting whole-house flushing after the repair is encouraged.

SUMMARY AND NEXT STEPS

This article presents the results of water quality sampling of homes with LSLs during water, sewer, and road reconstruction activities. The results of this study highlight potential opportunities to improve field practices for both planned and emergency work that can affect LSLs. In addition, recommendations for the development and implementation of protocols to protect public health during and after those construction activities are provided. Extensive collaboration between water and health agencies is essential to the success of this effort, and at the time of this writing, policymakers were deliberating on how best to incorporate full LSL replacement into projects for all homeowners.

ACKNOWLEDGMENT

Employees in every section of Milwaukee Water Works have contributed to developing and implementing the public health protections described here. Success would have been impossible without Laura Daniels, Dave Goldapp, Jamieson Koestler, Jason Otto, Patrick Pauli, Rosalind Rouse, Sherrie S[illegible], and Department of Public Works Commissioner Ghassan Korban. Colleagues at the Milwaukee Health Department (Paul Biedrzycki, Sarah DeRoo, Ben Jamer, Lindsey Page, and Marisa Stanley); Wisconsin Division of Health Services (Krista Christensen, Rob Irving, Jeff Phillips, Carrie Tomasallo, Robert Thiboldeaux, Meghan Walsh, and Mark Werner); Wisconsin Department of Natural Resources (Jill Jonas [retired] and Steve Elmore), and the US Environmental Protection Agency (Miguel delToral) provided valuable input and guidance throughout the project.

ABOUT THE AUTHORS

Carrie M. Lewis *is superintendent of Milwaukee Water Works (MWW), 841 N. Broadway, Room 409, Milwaukee, WI 53202 USA; carrie.lewis@milwaukee.gov. She previously held the position of water quality manager for MWW and also worked for the City of Calgary (Alta., Canada) Water Works, where she pioneered the use of particle counting in drinking water treatment. Lewis served on the Federal Advisory Committee for the Revised Total Coliform Rule and is chair of the National Drinking Water Council. She is a recipient of the AWWA George Warren Fuller Award (2008). She received a BSc degree from McGill University, Montréal, Ont., Canada, and an MSc degree from the University of Calgary (Alta., Canada).* ***Lon A. Couillard*** *is the water quality manager,* ***Patricia J. Klappa*** *is the water quality operations manager, and* ***Terrence B. Vandenbush*** *is the water quality analyst at MWW.*

http://dx.doi.org/10.5942/jawwa.2017.109.0016

REFERENCES

Cornwell, D. & Brown, R., 2015. *Evaluation of Lead Sampling Strategies.* Water Research Foundation, Denver.

Lead and Copper Working Group, 2015. Report of the Lead and Copper Rule Working Group to the National Drinking Water Advisory Council. USEPA, Washington.

MWW (Milwaukee Water Works), 2016. Protocol for Activities That Impact Lead Water Services.

MWW, 2015. How to Sample Water to Profile Water Quality From the Tap to the Water Main. www.youtube.com/watch?v=t1Rmf7dcms0 (accessed Sept. 29, 2016).

AWWA RESOURCES

- High-Velocity Household and Service Line Flushing Following LSL Replacement. Brown, R.A. & Cornwell, D.A., 2015. *Journal AWWA*, 107:3:E140. Product No. JAW_0081171.
- Role of the Water Main in Lead Service Line Replacement: A Utility Case Study. Camara, E.; Montreuil, K.R.; Knowles, A.K.; & Gagnon, G.A., 2013. *Journal AWWA*, 105:8:E423. Product No. JAW_0078472.

These resources have been supplied by *Journal AWWA* staff. For information on these and other AWWA resources, visit www.awwa.org.